An Association between Fine Particles and Asthma Emergency Department Visits for Children in Seattle

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Asthma is the most common chronic illness of childhood and its prevalence is increasing, causing much concern for identification of risk factors such as air pollution. We previously conducted a study showing a relationship between asthma visits in all persons < 65 years of age to emergency departments (EDs) and air pollution in Seattle, Washington. In that study the most frequent zip codes of the visits were in the inner city. The Seattle-King County Department of Public Health (Seattle, WA) subsequently published a report which showed that the hospitalization rate for children in the inner city was over 600/100,000, whereas it was < 100/100,000 for children living in the suburbs. Therefore, we conducted the present study to evaluate whether asthma visits to hospital emergency departments in the inner city of Seattle were associated with outdoor air pollution levels. ED visits to six hospitals for asthma and daily air pollution data were obtained for 15 months during 1995 and 1996. The association between air pollution and childhood ED visits for asthma from the inner city area with high asthma hospitalization rates were compared with those from lower hospital utilization areas. Daily ED counts were regressed against fine particulate matter (PM), carbon monoxide (CO), sulfur dioxide, and nitrogen dioxide using a semiparametric Poisson regression model. Significant associations were found between ED visits for asthma in children and fine PM and CO. A change of 11 µg/m^3 in fine PM was associated with a relative rate of 1.15 [95% confidence interval (CI), 1.08–1.23]. There was no stronger association between ED visits for asthma and air pollution in the higher hospital utilization area than in the lower utilization area. These findings were seen when estimated $PM_{2.5}$ concentrations were below the newly adopted annual National Ambient Air Quality Standard of 15 µg/m^3. *Key words:* air pollution, asthma, carbon monoxide, children, emergency departments, nitrogen dioxide, particulate matter. *Environ Health Perspect* 107:489–493 (1999). [Online 6 May 1999]
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Asthma is the most common chronic illness in children and the cause of most school absences (*1*). The rate of hospitalization for asthma has been increasing in children < 18 years of age (*2*). The primary increases in asthma morbidity are observed in minority populations in urban areas (*3*). When focusing on the inner city, 8–12% of children under 18 years of age have asthma (*4*). Many airborne factors can aggravate asthma, including cigarette smoke (*5*), dust mites, molds, cold air, animal dander (*6*), and cockroaches (*7*). Additionally, increases in air pollution are associated with exacerbation of asthma as measured by decreased lung function values and respiratory symptoms (*8–10*), shortness of breath (*11*), emergency department (ED) visits (*12–18*), and hospitalizations (*19,20*). Thus there is concern that air pollution is aggravating childhood asthma (*21,22*).

Seattle, Washington, is a hilly coastal city with a moderate climate. It is currently in compliance with all U.S. Environmental Protection Agency (EPA) air pollution standards. In Seattle, three studies have been conducted that found associations between the exacerbation of asthma and airborne particulate matter (PM). A study conducted during the heating season in a wood smoke impacted area found a significant association between decreased lung function in elementary school children with asthma and dry light scattering (σ_{sp}), a measure of fine PM (*8*). Another study carried out in Seattle from 1989 to 1990 found significant associations between both PM ≤ 10 µm in aerodynamic diameter (PM_{10}) and light-scattering values (particles approximately ≤ 1.0 µm) and ED visits for asthma for patients aged 65 years and younger (*12*). Most recently, a study of hospital admissions for asthma found an estimated 4–5% increase in admission rate associated with several measures of PM air pollution [PM_{10}, particulate matter ≤ 2.5 µm in aerodynamic diameter ($PM_{2.5}$), and the coarse fraction PM_{10}–$PM_{2.5}$] (*20*). Sources of PM in Seattle include wood smoke, gasoline and diesel vehicles, resuspended road dust, and industry (*23*). A source apportionment study of PM_{10} in Seattle in 1991–1992 found that during the heating season, 80% of PM in residential areas originated from wood-burning devices (*24*). Concentrations of all measured air pollutants have been decreasing in Seattle over the last decade (*25*).

The Seattle-King County Health Department (Seattle, WA) carried out a survey from 1987 to 1996 on asthma hospitalization rates for children in Seattle and surrounding areas using the Comprehensive Hospital Abstract Reporting System and found > 50% higher hospitalization rates in central and southeast Seattle (the inner city) as compared to other districts around Seattle (*26*). The present study examined whether there was a stronger association between air pollution and ED visits for asthma for children in the inner city area than for other children in Seattle using the same hospitals and found that there was not.

Methods

Health data. Daily ED visits for asthma were obtained from six hospitals in central and southeast Seattle from 1 September 1995 to 31 December 1996. Permission for use of the hospital data was obtained from the University of Washington Human Subjects Office in Seattle. Four of the six hospitals were downtown; the other two were located within 12 km of central Seattle (Figure 1). The total number of daily visits were compiled based on the *International Classification of Disease, Ninth Revision* (World Health Organization, Geneva) codes for asthma (493.01–493.99). Only data for patients under the age of 18 who lived in a 36-zip

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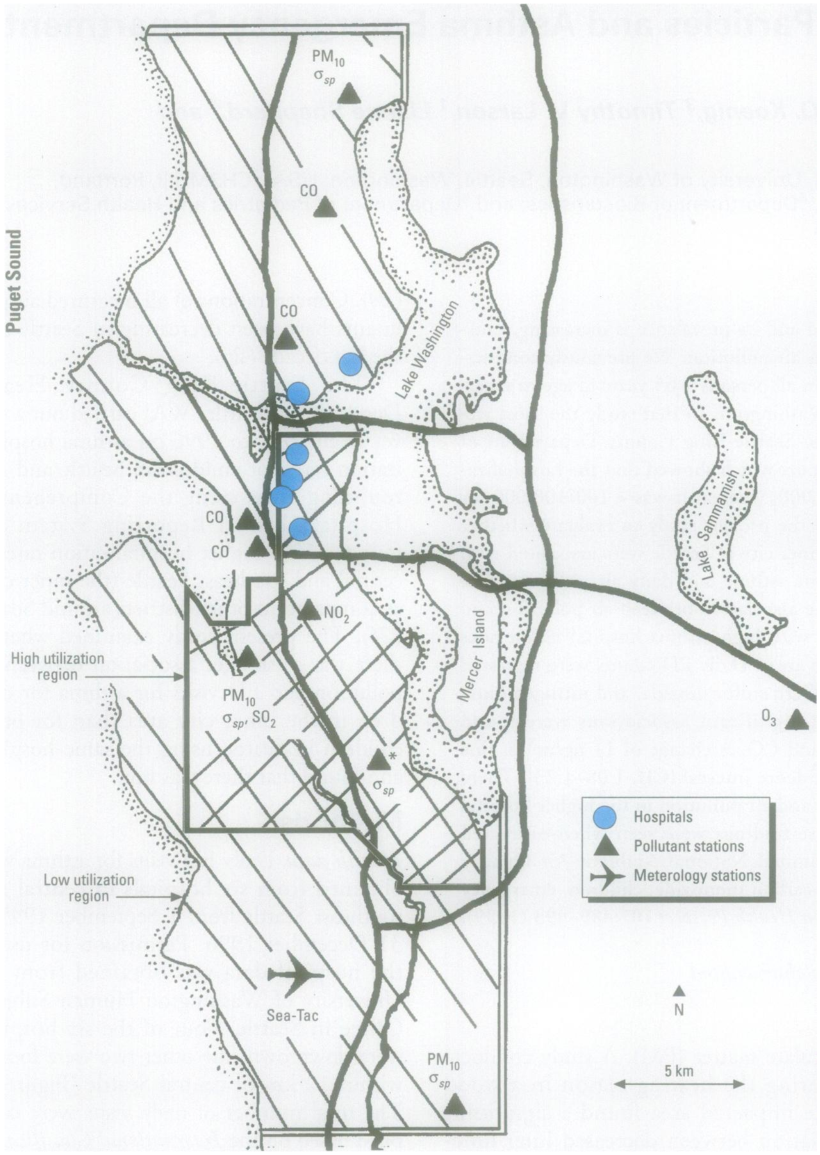

Figure 1. Map of study area showing the air pollution monitoring sites and the high and low emergency department asthma utilization regions. Abbreviations: PM_{10}, particulate matter ≤ 10µm in aerodynamic diameter; σ_{sp}, dry light scattering.
*Additional station that operated from February 1996 to January 1997.

code region were used. The zip code region contained the six hospitals and was limited to an area between the air monitoring stations to the north and south of the central area identified in the hospitalization survey (Figure 1). The 36 zip codes in that region were divided into a high and low utilization density based on the childhood ED visits for asthma. The top 20th percentile zip codes were designated as the high ED asthma utilization areas (seven zip codes). The rest of the zip codes were designated as the low ED asthma utilization areas (29 zip codes). The association between air pollution and ED asthma visits was evaluated for the entire study region (36 zip codes), as well as separately for the high and low ED utilization regions (Figure 1).

Atmospheric data. Air quality data were obtained from the Puget Sound Air Pollution Control Agency (Seattle, WA) and the state of Washington Department of Ecology (WDOE, Olympia, WA). Daily PM_{10} and dry light scattering data (σ_{sp}) were available at three sites—north, central, and south Seattle. Dry light scattering coefficient obtained from an integrating nephelometer most efficiently measures particles between 0.2 and 0.9 µm (*27*), which makes it a measure of the concentration of PM < 1 µm. Carbon monoxide (CO) values were obtained from four sites within the Seattle study region. Sulfur dioxide (SO_2) concentrations were measured at one site in central Seattle. Nitrogen dioxide (NO_2) and ozone data were obtained from the WDOE for a site in central Seattle and at a site 20 km east of Seattle, respectively. Because the health data collected for this study only covered one ozone season (April–October) there were sufficient ozone data for our model. In addition, the photochemical belt where ozone concentrations are measured is 20 km east of the area where children in this study resided.

For pollutants measured at multiple sites, a daily arithmetic average was calculated and used in the time–series analyses. The appropriate averaging time for each pollutant was based on national and state air quality standards. A 24-hr average was used for measures of PM. A 1-hr average was used for SO_2 to reflect the WDOE 1-hr standard of 400 ppb for SO_2. Because there is only an annual National Ambient Air Quality Standard (NAAQS) for NO_2, we selected the daily maximum 1 hr and daily average concentration for this pollutant. A number of studies have used the daily maximum 1 hr NO_2 concentration for time–series analyses (*14,15,28*). We assumed that CO was a general indicator of the build up of air pollution and we used an averaging time that matched the PM measurements (24 hr). Dew point temperature and average daily temperature data were collected from the Seattle Tacoma International Airport by the National Oceanic and Atmospheric Administration National Climatic Data Center (Figure 1); 24-hr averages were used for these meteorologic variables.

Statistical analysis. The ED visits for asthma were regressed on predictor and confounding variables using a semiparametric Poisson regression model, a method of choice in recent studies (*20,29*). All analyses were conducted with the S-PLUS statistical package (StatSci, Seattle, WA) using a generalized additive model (*30*). Base models were first constructed that adjusted for potential confounding factors using day-of-week indicator variables, smooth functions for time trends, temperature, and dew point temperature. The smooth function for time trends used a smoothing spline (*31*) that was approximately equivalent to a 2-month moving average. The degrees of freedom for the smoothing splines for temperature and dew point temperature were selected based on minimizing the degree of freedom adjusted deviance (*32*). After the base models were created for each of the three utilization areas (high, low, and entire area), the air pollution exposure variables were evaluated by adding them individually into the model. The final models were evaluated for overdispersion and autocorrelation. Additionally, the assumption of a linear dose response was evaluated using a smooth function.

The ED visits for asthma were assumed to be precipitated by either the same-day air pollution or air pollution levels up to 4 days before the visit (0- to 4-day lags). These lag times are consistent with that reported by Canny and colleagues (*33*) who found 84% of the asthmatic children had symptoms for 72 hr or less prior to arrival to the ED.

Results

Table 1 shows a summary of pollutant concentrations in this study. Table 2 summarizes the correlations between the exposure variables that were used. The PM_{10} and light-scattering measurements were highly correlated (r = 0.82). CO was also correlated with these PM measurements, but not with NO_2 or SO_2. An additional nephelometer was placed in south Seattle prior to this study to determine whether the inner city area fine PM values correlated with the other fixed PM monitors (Figure 1). The light-scattering measurements from the inner city monitor were highly correlated with the other monitors in the network, with a correlation coefficients ranging from 0.75 to 0.85.

The average number of ED visits for asthma in our study for children < 18 years of age was 1.8 per day, with a maximum of nine visits on any day. This number is low because we restricted the study area to the inner city and surrounding areas. The age distribution of the ED visits for asthma in children < 18 years of age is shown in Table 3. The majority of the ED visits were for children younger than 5 years of age. This age group accounted for 55 and 54% of the asthma visits for the high and low utilization regions, respectively. When comparing asthma ED visits between the two study areas, the high utilization area accounted for 41% of all the asthma ED visits (seven zip codes).

The association between air pollution and increased ED visits for asthma was evaluated in the three utilization regions. Significant associations between increased ED visits for asthma and air pollution were found across the utilization regions (Table 4). Relative rates were calculated for an interquartile range (IQR; 75–25th percentile) increase in pollutant concentration. Fine particles measured as light-scattering coefficient (σ_{sp}) were significantly associated with increased ED asthma visits in children from all three zip code areas with relative rate increases ranging from 1.13 to 1.16 across the study regions. PM_{10} and CO had similar relative rates over the study regions and were significantly associated with ED visits for asthma in the low utilization area and in the total study area. The daily 1-hr maximum SO_2 and NO_2 were not significantly associated with an increase in ED visits for asthma for any of the study areas. The association between ED visits for asthma and ozone was only determined for the entire study area because of the large number of missing data (45% of the days). Ozone was not significantly associated with ED visits for asthma; the relative rate was 1.02 [95% confidence interval (CI), 0.98–1.05] for an IQR of 4.6 ppb in the maximum daily running 8-hr average.

Multipollutant models containing either PM measurement (light scattering or PM_{10}), SO_2, and NO_2 were also analyzed for the entire study region using a 1-day lag. CO was excluded from the multipollutant model because it was assumed to be a surrogate for stagnant conditions. The relative rate for light scattering and PM_{10} remained significant with relative rates of 1.17 (CI, 1.08–1.26) and 1.14 (CI, 1.04–1.26), whereas the SO_2 and NO_2 terms were not significantly associated with an increase in ED visits for asthma (data not shown).

The highest PM concentrations were observed during the winter heating season, as was seen in three earlier studies in Seattle (*8,12,20*) (Figure 2). Initial analyses showed that 24 and 25 December 1995 were influential data points in the regression because of the high measured PM concentrations. To assess the impact of these data, we repeated the analyses with and without these 2 days to evaluate the effect of these atypically high PM concentrations (Figure 2). The relative rates for increased ED visits for asthma in the entire study area including and excluding 24 and 25 December were 1.11 (CI, 1.02–1.20) and 1.14 (CI, 1.05–1.24), respectively, for an 11.5-µg/m³ increase in PM_{10}. Relative rates for inclusion and exclusion of those dates for associations with light scattering were 1.10 (CI, 1.04–1.17) and 1.15 (CI, 1.07–1.23) for an IQR increase. These results show the relative rates remained significant with the inclusion of the influential dates, but the relative rate for light scattering decreased 5% with the inclusion of the two

Table 1. Summary of air pollutants and health end points (1 September 1995 to 31 December 1996).

Variable	Mean	SD	Minimum	Maximum	Missing (%)
Meteorology					
Temperature (°F), daily average	52.0	10.6	1.0	80.0	0.0
Dew point (°F), daily average	43.5	9.2	7.5	62.0	0.0
Air pollutants					
PM_{10} (µg/m³), three sites, daily average	21.7	10.0	8.0	69.3	0.0
σ_{sp} (m^{-1}), three sites, daily average	0.4[a]	0.3	0.1	2.7	0.0
SO_2 (ppb), maximum 1-hr	16.0	14.0	2.0	84.0	2.5
SO_2 (ppb), daily average	6.0	3.0	1.0	21.0	2.5
NO_2 (ppb), maximum 1-hr[b]	34.0	11.3	8.0	94.0	2.0
NO_2 (ppb), daily average[b]	20.2	7.1	5.0	47.0	2.0
Average CO (ppm), daily average	1.6	0.5	0.6	4.1	0.0
O_3 (ppb), daily maximum 8-hr	30.4	14.9	2.5	83.1	45.0
Health end points (daily ED visits)					
High utilization	0.8	0.8	0.0	5.0	0.0
Low utilization	1.1	1.2	0.0	7.0	0.0
Total	1.8	1.6	0.0	9.0	0.0

Abbreviations: CO, carbon monoxide; ED, emergency department; NO_2, nitrogen dioxide; O_3, ozone; PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter; SD, standard deviation; SO_2, sulfur dioxide; σ_{sp}, dry light scattering.
[a]Approximately 12 µg/m³ fine PM (≤2.5 µm). [b]January 1995 to December 1996.

Table 2. Bivariate correlation among exposure variables (1 September 1995 to 31 December 1996).

	CO[a]	PM_{10}[a,b]	σ_{sp}[a]	NO_2[c]	NO_2[a]	SO_2[c]	SO_2[a]
CO[a]	1.00	0.74	0.74	0.47	0.66	0.15	0.32
PM_{10}[a,b]		1.00	0.82	0.56	0.66	0.24	0.43
σ_{sp}[a]			1.00	0.41	0.59	0.19	0.34
NO_2[c]				1.00	0.85	0.22	0.37
NO_2[a]					1.00	0.45	0.25
SO_2[c]						1.00	0.82
SO_2[a]							1.00

Abbreviations: CO, carbon monoxide; NO_2, nitrogen dioxide; PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter; SO_2, sulfur dioxide; σ_{sp}, dry light scattering.
[a]Daily average. [b]Light scattering. [c]Daily maximum 1-hr.

Table 3. Emergency department visits (%) for asthma by age group and utilization area (September 1995–December 1996).

	Utilization[a]		All
Age (years)	High[b]	Low[c]	zip codes
< 5	204 (55)	287 (54)	491 (55)
5–11	117 (32)	172 (33)	289 (32)
12–17	50 (13)	70 (13)	120 (13)
Total	371 (100)	529 (100)	900 (100)
Daily visits (average)	0.8	1.1	1.8
Utilization[a] (average)	23	8	11

[a]Utilization/day/10,000 population. [b]Seven zip codes. [c]Twenty-nine zip codes.

Table 4. Relative rates between emergency department visits for asthma for an IQR increase in pollutant concentration.

Pollutant	IQR	High	Low	All
σ_{sp} [a,b]	0.3 (m^{-1}/10^{-4})[b]	1.13 (1.02–1.24)	1.16 (1.06–1.27)	1.15 (1.08–1.23)
PM_{10} [a]	11.6 µg/m^3	1.11 (0.98–1.25)	1.14 (1.02–1.27)	1.14 (1.05–1.23)
CO [a]	0.6 ppm	1.04 (0.93–1.16)	1.15 (1.05–1.28)	1.10 (1.02–1.19)
NO_2 [c]	12 ppb	1.05 (0.96–1.14)	1.06 (0.99–1.14)	1.05 (0.99–1.12)[d]
NO_2 [a]	9 ppb	0.88 (0.76–1.02)	1.10 (0.97–1.24)	0.99 (0.90–1.08)[e]
SO_2 [c]	12 ppb	0.99 (0.89–1.10)	1.09 (1.00–1.19)	1.02 (0.95–1.09)[d]
SO_2 [a]	3 ppb	0.92 (0.83–1.03)	1.09 (1.00–1.19)	0.97 (0.91–1.04)[e]

Abbreviations: CO, carbon monoxide; IQR, interquartile range; NO_2, nitrogen dioxide; PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter; SO_2, sulfur dioxide; σ_{sp}, dry light scattering. All associations are reported for the 1-day lag except those stated otherwise.
[a]Daily average. [b]Approximately 9.5 µg/m^3 of fine PM (≤ 2.5 µm). [c]Daily maximum 1-hr. [d]Zero-day lag. [e]Two-day lag.

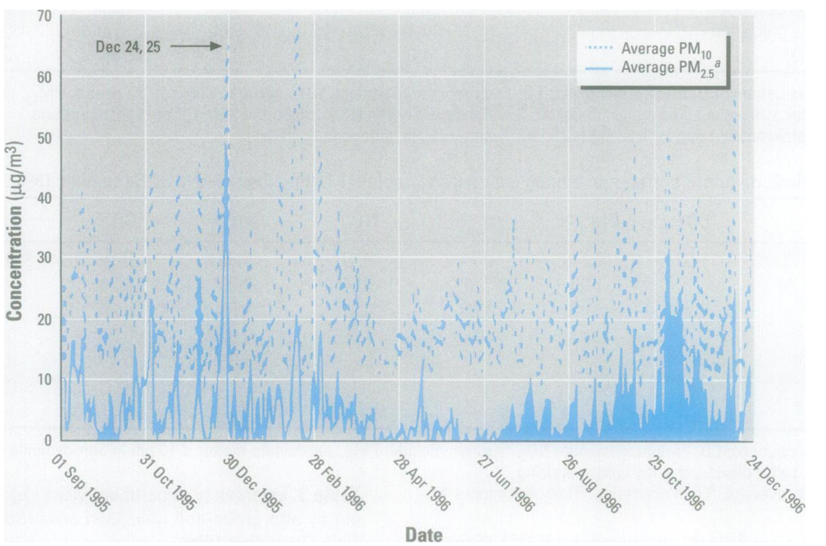

Figure 2. Time series of PM_{10} and $PM_{2.5}$ data. Abbreviations: $PM_{2.5}$, particulate matter ≤ 2.5 µm in aerodynamic diameter; PM_{10}, particulate matter ≤ 10 µm in aerodynamic diameter.
[a]Estimated from light-scattering data.

high concentration points. Additionally, the inclusion of 24 and 25 December 1995 caused the dose–response relationships for light scattering to show nonlinear behavior above values approximately equal to 40 µg/m^3 $PM_{2.5}$. Because these 2 days were holidays, the use of the ED visits for asthma may have been different from other days in the study. Based on the high influence and a potential holiday effect, these 2 days were not included in our primary analysis.

Discussion

We found significant associations between ED visits for asthma in children and PM_{10}, light-scattering measurement of fine PM, and CO. Light scattering, which is a measure of fine PM primarily < 1.0 µm in diameter, was significantly associated with ED visits for asthma in all the analyses. Additionally, PM_{10} and CO were significant predictors of ED asthma visits in the low utilization and for the combined utilization areas. The higher relative risk in this study as compared to the earlier results by Schwartz and colleagues (*12*) may be due to the fact that our population was restricted to individuals under the age of 18, a more susceptible group than the population at large.

We recognize that ED data from hospitals contain some misdiagnoses. Delfino and associates (*34*) found a good association between hospital summary data and chart review. The majority of cases in our study came from a single children's hospital specializing in diagnoses for childhood diseases.

The number of visits for the high utilization region (371) was less than the low utilization area (529) and likely did not achieve statistical significance for PM_{10} and CO because of the reduced number of events. Otherwise, the high and low utilization areas did not appear to have different associations between air pollution and increased ED visits for asthma. The estimated numbers of children under 18 years of age in the high utilization area and in the rest of Seattle were 6,921 and 100,895, respectively. However, we cannot compare the absolute number of visits for the two utilization areas because a given relative rate increase in ED visits in the high utilization area caused more absolute visits than in the low utilization area.

In this study, relative rates for light scattering in the low and high utilization areas were 13 and 16% for an IQR increase of approximately 10 µg/m^3 of fine PM. The light-scattering IQR was converted to represent $PM_{2.5}$ gravimetric mass based on colocated nephelometer and $PM_{2.5}$ monitors at the southernmost PM monitoring site (224 days, r = 0.86). The average concentration for the 15-month period of this study was approximately 12 µg/m^3 $PM_{2.5}$, a concentration below the new EPA annual standard (15 µg/m^3). PM_{10} was associated with a 14% increase in ED asthma visits for an increase of 12 µg/m^3 PM_{10}.

The association between increased asthma visits and CO was investigated in Anchorage, Alaska (*35*), Reno, Nevada (*36*), and Seattle (*20*). The Anchorage and Reno studies did not find a significant association between ED visits for asthma and CO; however, CO was associated with hospital admissions in Seattle (*20*). The Reno study used the highest hourly maximum level in their local air pollution network, and the Anchorage study used the daily average 8-hr maximum concentration during winter months. The Seattle hospital admission study (*20*) used the daily average of four monitoring stations. In the present study, we used a 24-hr average of four sites in our study region for the entire 15 months. Because CO has no biologically plausible mechanism for the exacerbation of asthma (*37*) we interpret it as a general indicator of air pollution. The significant association between increased ED visits for asthma and CO found in this analysis could result from the high correlation between CO and PM_{10} (0.74) as well as light scattering (0.74). To explore this possibility, a factor analysis of the physical and chemical nature of air pollution in Seattle was conducted on both the CO and particulate composition data collected previously (*38*) at the southernmost PM site in this study. Factor analysis with a varimax rotation has been used to both examine the colinearity among the various air pollutant variables and to identify important features of the variability in these pollutants (Table 5) (*39,40*). Main et al. (*38*) measured the composition of $PM_{2.5}$ or fine soil and coarse PM (PM_{10}–$PM_{2.5}$). Coarse and fine soil mass were reconstructed by adding the mass of the oxides of soil species (Si, Ca, Fe, and Ti) (*41*). Using these data we derived three factors which explained 95% of the variance and show that the variability in $PM_{2.5}$ composition is influenced by three factors: *a*) incomplete combustion products consisting of CO, elemental carbon, organic carbon, and soluble potassium (wood smoke marker); *b*) secondary aerosols consisting of ammonium and sulfate; and *c*) fine and coarse soil (Table 5). The light scattering

Table 5. Loadings from a factor analysis of the air pollution concentrations.[a]

	Factor 1	Factor 2	Factor 3
Percent of variance	55.2	25.2	15.2
Carbon monoxide	0.85	–	–
Elemental carbon	0.93	–	–
Organic carbon	0.95	–	–
Soluble potassium	0.96	–	–
Ammonium	–	0.94	–
Sulfate	–	0.96	–
Fine soil	–	–	1.00
Coarse soil	–	–	1.00

[a]Loadings < 0.5 are shown as dashes (–).

and PM_{10} data are correlated with the first factor scores, with correlation coefficients of 0.81 and 0.77, respectively. Note that CO is associated with the buildup of incomplete combustion-derived products including particulate organic carbon and particulate elemental carbon.

This study did not find a significant association between NO_2, SO_2, or ozone and increased ED asthma visits. The NO_2, SO_2, and ozone measurements are only taken at one site in the network and may be subject to a greater degree of exposure misclassification than the CO and PM pollutant measures that represent averages of three to four sites in the study area. In addition, the SO_2 concentrations were low, with a mean daily 1-hr maximum concentration of 6 ppb. Other investigators have reported that the peak hourly NO_2 concentration was significantly associated with increased ED visits for asthma during winter months in Northern California (*15*) and with increased ED visits and respiratory admissions in Athens, Greece (*28*). Peak hourly NO_2 was also associated with increased ED visits for asthma during both the winter and summer months in Barcelona, Spain (*14*). The average peak NO_2 concentrations in the Northern California, Athens, and Barcelona studies were 69 ppb, 50 ppb, and 58 ppb, respectively. These concentrations are significantly higher than the average peak hourly NO_2 concentration of 35 ppb observed in this study. Our finding of no significant association between ED asthma visits and maximum hourly SO_2 is consistent with the earlier Seattle study (*12*) and the study in Barcelona (*14*). The lack of a significant association between ED visits for asthma and ozone in this study may be due to the large number of missing measurements.

In summary, this study found a small but significant association between air pollution and increased ED visits for asthma in children in Seattle. PM and CO concentrations in this study were associated with increased childhood ED visits for asthma and represent the daily variation in incomplete combustion products including elemental carbon and organic carbon. Results from this study of a susceptible subpopulation show significant increases of ED asthma visits for children with daily $PM_{2.5}$ concentrations substantially below the newly adopted National Ambient Air Quality Standard of 15 μg/m annually (*42*).

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